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## SPECIFICATION

### 1. Title of the Invention

Photodetector

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### 2. Scope of Claims

(1) A photodetector of a structure in which a plurality of conductive-type layers (11) of reverse conductivity to a semiconductor substrate (10) are formed at prescribed intervals in the upper surface of said semiconductor substrate (10) and photoelectric converting portions using pn junctions are formed by said semiconductor substrate (10) and said reverse conductive-type layers (11),

characterized in that an energy gap increases continuously in the depth direction of said semiconductor substrate (10), the semiconductor substrate (10) has a potential gradient so that excess minority carriers move in the direction of the upper surface of said semiconductor substrate (10), and a photosignal charge recombining region (12) is provided to surround each of said plurality of reverse conductive-type layers (11).

(2) The photodetector according to claim 1, characterized in that, in place of said recombining region (12), an excess photosignal charge eliminating region (13) is provided to surround each of said plurality of reverse conductive-type layers (11).

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### 3. Detailed Description of the Invention

#### (Summary)

The present invention relates to the structure of a pn junction photoelectric converter of an infrared detector,

the object of which is to provide a photodetector configured from a pn junction array on a compound semiconductor comprising a photoelectric conversion structure that reduces signal charge crosstalk at least between the pn junctions,

the invention being constituted from a photodetector of a structure in which a plurality of conductive-type layers of reverse conductivity to a semiconductor substrate are formed at prescribed intervals in the upper surface of the semiconductor substrate and pn junction photoelectric converting portions are formed by the semiconductor substrate and the reverse conductive-type layers, the energy gap increasing continuously in the depth direction of the semiconductor substrate, the semiconductor substrate having a potential gradient so that the excess minority carriers move in the direction of the upper surface of the semiconductor substrate, and a photosignal charge recombining region being provided to surround each of the plurality of reverse conductive-type layers.

#### (Field of Industrial Application)

The present invention relates to a photodetector, and more particularly to the structure of a pn junction photoelectric converter of an infrared detector.

The demand in recent years for infrared detectors of higher performance has been accompanied by a demand for infrared detectors of greater miniaturization, increased pixel count and improved resolution. For improving the resolution, in a configuration of the pn junction photoelectric converters on the substrate, the pitch between the pixels (between the pn junctions) must be narrowed and, moreover, the photosignal charge crosstalk between the pixels must be reduced.

(Prior Art)

Conventional types of pn junction photodetector comprise a plurality of photoelectric converters configured from pn junctions formed on a substrate, and include a back surface incident-type on which infrared light is incident through the back surface, and a front surface incident-type on which infrared light is incident through the front surface. In back surface incident-type photodetectors, infrared light is photoelectrically converted at the back of substrate away from the pn junction, and then the signal charge due to the light is diffused within the substrate to the pn junction that serves as a signal readout portion. For this reason, in photodetectors in which the pixel pitch is narrowed for the purpose of improving resolution, signal charge crosstalk between adjacent pixels is unavoidable.

Thereupon, as shown in Fig. 8(a), in conventional photodetectors, for example, a pn junction photoelectric converting portion is formed by forming an n<sup>+</sup> region 2 in the upper surface of a p-type semiconductor substrate 1, and a high-concentration layer 3 of

a same conductive type (here, a p-type) as the semiconductor substrate 1 is provided around the photoelectric converting portion for forming a potential barrier in the semiconductor substrate 1.

As a consequence, as shown by the symbol 4 in Fig. 8(a), the diffusion of the signal charge produced by the photoelectric conversion of the infrared light incident through the back surface of the semiconductor substrate 1 to adjacent pixels (pn junctions) is blocked by the high-concentration layer 3.

On the other hand, in front surface incident-type photodetectors, signal light in the vicinity of the cutoff wavelength is absorbed and photoelectrically converted in the deep part of the substrate and, as a result, crosstalk (smear) occurs at long wavelengths and, in addition, blooming occurs for the same reason.

Thereupon, conventional front surface incident-type photodetectors comprise a high-concentration layer the same as that in Fig. 8(a), or a shield configured from aluminium (Al) or the like being formed on the front surface excluding the pn junction photoelectric converting part.

#### (Problems to be Solved by the Invention)

However, because the adoption of the structure shown in Fig. 8(a) is difficult in photodetectors that employ a compound semiconductor as a substrate on the surface of which photoelectric converters are one-dimensionally or two-dimensionally arrayed because it is difficult to form the high-concentration layer deeply in the substrate, the pn junction photoelectric converter is configured by,

for example, the forming of an  $n^+$  region 6 in the surface of a p-type semiconductor substrate 5 and the provision of a physical separating groove 7 around the photoelectric converter as shown in Fig. 8(b), or else the pn junction (pixel) pitch is increased, or the carrier concentration of the semiconductor substrate is increased to reduce the diffusion length of the signal charge.

For this reason, when the pixel number in a photodetector that employs a compound semiconductor substrate is increased, the pixel pitch (pn junction pitch) cannot be narrowed to a prescribed value or below and this leads to the enlarging of the shape of the photodetector. In addition, the formation process in the method for the forming of the separating groove 7 described above is inherently difficult to implement and results in a significant reduction in yield. A further problem is the worsening of the pn junction characteristics that results from the increase in the carrier concentration of the semiconductor substrate. In addition, because a shield formation step is required, a greater number of steps are used to fabricate a front surface incident-type photodetector.

With the foregoing problems in mind, it is an object of the present invention to provide a photodetector configured from a pn junction array on a compound semiconductor comprising a photoelectric conversion structure that reduces signal charge crosstalk at least between the pn junctions.

(Means for Solving the Problem)

Fig. 1 is an explanatory diagram of the principles of the invention according to claim 1 (hereinafter referred to as the first invention). In Fig. 1(A), which is a main part schematic cross-sectional diagram of the first invention, 10 denotes a semiconductor substrate, 11 denotes a reverse conductive-type layer, and 12 denotes a recombining region. A plurality of reverse conductive-type layers 11 are formed at prescribed intervals in the front surface of the semiconductor substrate 10 and pn junction photoelectric converting portions are formed by the semiconductor substrate 10 and the reverse conductive-type layers 11.

As shown in Fig. 1(B), in the first invention of a photodetector of a structure such as this, the energy gap increases continuously in the depth direction of the semiconductor substrate 10, the semiconductor substrate 10 has a potential gradient so that excess minority carriers move in the direction of the upper surface of the semiconductor substrate 10, and a photosignal charge recombining region 12 is provided to surround each of the plurality of reverse conductive-type layers 11.

In addition, Fig. 2 is an explanatory diagram of the principles of the invention according to claim 2 (hereinafter referred to as the second invention). Identical symbols have been assigned to constituent sections of this drawing identical to those of Fig. 1 and, accordingly, the description thereof has been omitted. In the main part schematic cross-sectional diagram of the second invention as shown in Fig. 2(A), in addition to the reverse conductive-type layers 11, diffusion layers 13 are formed on the semiconductor substrate 10,

and pn junction charge eliminating regions are formed by the diffusion layers 13 and the semiconductor substrate 10. That is, instead of the recombining region 12 of Fig. 1(A), the second invention comprises a charge eliminating region.

5 In addition, in Fig. 2(A), an insulating film 14 that excludes part of the reverse conductive-type layer 11 is formed on the upper surface of the semiconductor substrate 10 and, furthermore, an electrode 15 is provided thereon in a position corresponding to the diffusion layer 13.

10 (Action)

In the first invention shown in Fig. 1, when the semiconductor substrate 10 is a p-type substrate and the carrier concentration of the semiconductor substrate 10 is constant, as shown in Fig. 1(B) a potential  $E_c$  of a conduction band works in a direction to accelerate  
15 excess electrons on the conduction band from the back surface of the semiconductor substrate 10 in the direction of the reverse conductive-type layer 11. On the other hand, a potential  $E_v$  of a valence band is constant from a depletion layer in the vicinity of the reverse  
20 conductive-type layer 11 to the back surface of the semiconductor substrate 10.

Here, the electric field produced by the above-described potential gradient of the conduction band is set such that the electron velocity approximates the thermal velocity. In this case, the signal  
25 charge (electrons) generated by the light ( $h\nu$ ) incident on the semiconductor substrate 10 is accelerated by the potential gradient of

the conduction band as shown in Figs 1(A) and (B), and it arrives at the front surface of the semiconductor substrate 10 comprising pn junctions having been diffused negligibly in the lateral direction, and then being diffused laterally at the front surface as shown by the symbol I of Fig. 1(A).

Moreover, because a recombining region 12 is provided between the pn junctions in the first invention, the signal charge diffused in the lateral direction at the substrate surface is absorbed by the recombining region 12 with infinite surface recombining velocity. So.

In addition, although the second invention shown in Fig. 2 is similar to the first invention in that, as shown in Figs. 2(A), (B), the signal charge (electrons) is accelerated by the potential gradient of the conduction band and arrives at the substrate surface having been diffused negligibly in the lateral direction, and then being diffused laterally, in this invention, the signal charge diffused in the lateral direction is absorbed by the pn junction eliminating region formed by the diffusion layer 13 and semiconductor substrate 10.

Furthermore, in the present invention, as shown in Figs. 2(A) and (C), by the formation of a surface inversion region 16 in the semiconductor substrate 10 directly below the electrode 15 as shown in Fig. 2(C) using an MIS electrode configured from the electrode 15, the insulating film 14, and the semiconductor in the periphery of the charge eliminating region, the area of the charge eliminating region can be adjusted by the voltage applied from a voltage source 17 to the electrode 15. Accordingly, in the present invention, the elimination

quantity of charge can be adjusted in response to the intensity of the incident light by controlling the voltage applied to the electrode 15 in response to the intensity of the incident light.

Here, the semiconductor substrate 10 may be an n-type rather than a p-type and, in this case, when the energy gap increases continuously in the depth direction from the substrate upper surface on which the pn junctions are formed and, in addition, when the carrier concentration of the substrate is constant in the substrate, the potential  $E_v$  of the valence band shown in Fig 3 works to accelerate the excess positive holes of the valence band from the back surface to the front surface of the substrate. The  $E_F$  in Fig. 3 denotes the Fermi level.

#### (Embodiments)

Embodiments of the present invention will be hereinafter described. Fig. 4 is a configuration diagram and an energy band diagram of a first embodiment of the present invention: (A) is a top plan view, (B) is a vertical cross-sectional view along the line X-X' of (A), and (C) is an energy band diagram in the cross section along the line Y-Y' of (B). In this embodiment, which is an embodiment of the first invention, a p- $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$  substrate 20 which is a mixed crystal of the II-IV semiconductor is employed as a semiconductor substrate 10.  $n^+$  diffusion layers 21 (equivalent to 11 of Fig. 1) are formed at prescribed intervals on the upper surface of the substrate 20, and photoelectric converting portions are formed by the pn junctions by the  $n^+$  diffusion layers 21 and substrate 20.

In addition, as shown in Figs. 4(A) and (B), a zinc sulphide (ZnS) film 22 is formed on the upper surface of the substrate 20 as a protective insulating film with respective parts of the plurality of  $n^+$  diffusing layers 21 and other prescribed portions being exposed. Signal extracting electrodes 23 configured from, for example, indium (In) are formed in the openings of the ZnS film 22 above the  $n^+$  diffusing layers 21, and ohmic contact metal electrodes 24 configured from, for example, gold (Au) are formed in the other openings. As is clear from Figs. 4(A) and (B), the ohmic contact metal electrodes 24 are formed between the adjacent photoelectric converters by pn junction and constitute the recombining region 12 described above.

In addition, in this embodiment, taking the composition ratio  $x$  of the  $Hg_{1-x}Cd_xTe$  substrate 20 at the pn junction part with the diffusion layer 21 as 0.210 (energy band  $E_{g1} = 0.1001\text{eV}$ ), the composition ratio  $x$  increases linearly in the depth direction of the substrate from the pn junction part reaching 0.240 ( $E_{g2} = 0.1483\text{eV}$ ) at the position of the substrate 20 of film width  $10\mu\text{m}$ . Furthermore, when the carrier concentration of the p-type  $Hg_{1-x}Cd_xTe$  substrate 20 is a constant at  $1 \times 10^{16}\text{cm}^{-3}$ , as shown in the energy band diagram of Fig. 4(C), the potential  $E_v$  gradient of the valence band becomes small, and the energy gap difference lies almost exclusively at the conduction band side, and therefore the potential  $E_c$  gradient of the conduction band increases, and the electric field produced by the potential gradient of the conduction band in this case is approximately  $50\text{V/cm}(\cong(E_{g2} - E_{g1})/10\mu\text{m})$ .

The mobility of the conduction band electrons is  $2 \times 10^5 \text{ cm}^2/\text{V/s}$  at 77K and, therefore, the electron velocity, which is expressed as a product of the electron mobility and the electric field, is  $1 \times 10^7 \text{ cm/s}$  and approximates the thermal velocity.

5           As a consequence, as shown by the symbol 25 in Fig. 4(B), the signal charge generated at the back surface by the infrared light incident on the back surface of the p-type  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$  substrate 20 arrives at the substrate front surface comprising pn junction parts without having been diffused in the lateral direction, after which it is  
10          diffused in the lateral direction at the substrate surface before being vanished at the recombining region by the ohmic contact metal electrodes 24.

          Accordingly, the signal charge flowing into any one pn junction is from the region surrounded by the ohmic contact metal electrode 24  
15          only, and so mixing of the signal charge between adjacent pn junctions (pixels) is eliminated. Accordingly, crosstalk does not occur between signals produced by the photoelectric conversion by the pn junctions of the incident infrared light and, as a result, a distinct infrared image is able to be produced.

20          A manufacturing method of the present embodiment will be described with reference to Fig. 5. Identical symbols have been assigned to constituent sections of this drawing identical to those of Fig. 4.

25          First, mercury (Hg), cadmium (Cd) and tellurium (Te) are epitaxially grown on a p-type CdTe substrate by a metal-organic vapor-phase epitaxial growth method (MOCVD method), the

composition ratio  $x$  of Cd with respect to Hg changes over time and, as described above, the further in the substrate depth direction from the pn junction parts of the substrate upper surface, the greater the composition ratio of Cd to Hg. As a consequence, a p-type  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$  substrate 20 of thickness  $10\mu\text{m}$  is fabricated.

Next, the upper surface of the substrate 20 is covered by a resist 27 of a prescribed pattern as shown in Fig. 5(A), and then  $n^+$  diffusion layers 21 of prescribed depth are formed in the upper surface part of the substrate 20 not covered by the resist 27 by the high-concentration ion injection of boron ions ( $\text{B}^+$ ) from above the resist 27. Photoelectric converting portions (photodiodes) are formed by the pn junctions between the  $n^+$  diffusion layers 21 and substrate 20.

Next, as shown in Fig. 5(B), following the removal of the resist 27, a ZnS film 22 of film thickness  $1\mu\text{m}$  is formed as a protective insulating film over the whole of the upper surface of the substrate 20 by sputtering or deposition. Thereafter, as shown in Fig. 5(C), the ZnS film 22 is etched by a photolithography step to form openings (contact holes) 22a that partially expose the  $n^+$  diffusion layers 21 and openings (contact holes) 22b that expose the substrate upper surface between the pn junction parts.

Next, as shown in Fig. 5(D), In is deposited in only the openings 22a to form signal charge extracting electrodes 23, and then as shown in Fig. 5(E), Au is deposited in the openings 22b to form ohmic contact metal electrodes 24.

A second embodiment of the present invention will be hereinafter described. Fig. 6 shows a configuration diagram and an

energy band diagram of a second embodiment of the present invention: (A) is a top plan view, (B) is a vertical cross-sectional view along the line X-X' of (A), and (C) is an energy band diagram in the cross section along the line Y-Y' of (B). Fig. 6 shows an embodiment of the second invention; identical symbols have been assigned in this drawing to constituent sections identical to those of Fig. 4 and, accordingly, the explanation of these sections has been omitted.

The symbol 31 in Figs. 6(A) and (B) denotes  $n^+$  diffusion layers formed between the pn junction parts, corresponding to the diffusion layers 13 of Fig. 2. In addition, the symbol 32 denotes a protective insulating film corresponding to the protective insulating film 14, that has openings that expose parts of the  $n^+$  diffusion layers 21 only. The symbol 33 denotes an electrode configured from aluminium (Al) corresponding to the electrode 15 formed on the  $n^+$  diffusion layers 21.

This embodiment comprises a substrate 20 identical to the first embodiment and, therefore, as shown in Fig. 6, the energy band diagram of the substrate 20 is identical to the energy band diagram shown in Fig. 4(C). As a consequence, the signal charge generated by the infrared light incident on the back surface of the p-type  $Hg_{1-x}Cd_xTe$  substrate 20 moves straight from the substrate back surface to the front surface as shown by the symbol 34 in Fig. 6(B) and is diffused at the substrate upper surface and eliminated by the pn junctions of the  $n^+$  diffusion layers 31 and substrate 20.

As a consequence, the advantages of the present embodiment is identical to that of the first embodiment. Furthermore, in the present embodiment, when voltage is applied from a voltage source 35 to the

electrode 33 of an MIS electrode structure forming the surface of the semiconductor substrate 20 directly below the electrode 33 in an inverted state, the charge eliminating pn junction area can be effectively increased because this inverted state region also possesses a charge eliminating function.

Moreover, the area of the inversion region of the substrate upper surface changes in response to the voltage applied to the electrode 33. Therefore, by varying the voltage of the voltage source 35 in response to the intensity of the incident infrared light and, when the intensity of the incident infrared light is strong, by adjusting the voltage applied to the electrode 33 to a high voltage, the surface inversion region can be increased to ensure that almost all of the excess signal charge is absorbed. Accordingly, based on the present embodiment, blooming can be also prevented.

A manufacturing method of the second embodiment will be described hereinafter with reference to Fig. 7. Identical symbols have been assigned in this drawing to constituent sections identical to those of Fig. 6. Fig. 7(A) is identical to the manufacturing step shown in Fig. 5(A) and shows the formation of  $n^+$  diffusion layers 21 on a substrate 20. Next, as shown in Fig. 7(B), after removal of a resist 27, a patterned resist 38 is newly provided on the substrate 20 to expose the upper surface of the substrate 20 between the adjacent  $n^+$  diffusion layers 21 and, using the resist 38 as a mask,  $n^+$  diffusion layers 31 are formed by the high-concentration ion injection of  $B^+$  ions.

Next, after removal of the resist 38, as shown in Fig. 7(C), an ZnS film 32 is formed by a method identical to the manufacturing step

shown in Fig. 5(B), and then as shown in Fig. 7(D), openings 32a are formed by a method identical to the manufacturing step shown in Fig. 5(C). Here, of the  $n^+$  diffusion layers 21 and 31, the openings 32a expose only part of the  $n^+$  diffusion layers 21 used for the forming of the photoelectric converting portions.

Next, as shown in Fig. 7(E), metal electrodes 33 configured from Al of film thickness of, for example,  $0.5\mu\text{m}$  are formed in a position of the ZnS film 32 above the  $n^+$  diffusion layers 31. Next, as shown in Fig. 7(F), signal charge extracting electrodes 23 by using In are patterned by a photolithography step and, finally, as shown in Fig. 7(G), a metal electrode 39 configured from Au is formed on the outer side of the outermost electrode 33 by deposition. The electrode 39 is earthed to facilitate the photoelectric conversion by the pn junction parts.

Here, the step for the electrodes 33 shown in Fig. 7(E) is not essential. Despite the absence of an MIS electrode in this case, because the signal charge diffused at the substrate upper surface still flows into the pn junctions between the  $n^+$  diffusion layers 31 and substrate 20 and is still eliminated therefrom, crosstalk between pixels can be reduced.

In addition, although a  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$  substrate 20 is described in these embodiments, the substrate may be configured by a ternary system of II-VI, III-V, IV-VI semiconductors.

(Effect of the Invention)

As is described above, the advantages of the present invention include, because signal charge is diffused only on the substrate upper surface and, in addition, the signal charge diffused on the substrate upper surface is absorbed and eliminated by a recombining region or pn junction eliminating region provided between the photoelectric converting portions, the prevention of crosstalk between pixels and, accordingly, the greater narrowing of the pixel pitch than that possible in the prior art and, in addition, because there is no separating groove formed, greater miniaturization and higher pixel count than that possible in the prior art.

#### 4. Brief Description of the Drawings

Fig. 1 is an explanatory diagram of the principles of a first invention;

Fig. 2 is an explanatory diagram of the principles of a second invention;

Fig. 3 is an explanatory diagram of the principles of the present invention when the semiconductor substrate is an n-type;

Fig. 4 is a configuration diagram and energy band diagram of a first embodiment of the present invention;

Fig. 5 is a cross-sectional diagram of the manufacturing steps of a first embodiment of the present invention;

Fig. 6 is a configuration diagram and energy band diagram of a second embodiment of the present invention;

Fig. 7 is a cross-sectional diagram of the manufacturing steps of a second embodiment of the present invention;

Fig. 8 is a diagram of the main part structure of example conventional photodetectors.

In the drawings,

- 5        10 denotes a semiconductor substrate,
- 11 denotes a reverse conducting-type layer,
- 12 denotes a recombining region,
- 13 denotes a diffusion layer that serves as an eliminating region,
- 14 denotes an insulating film,
- 10       15 denotes an electrode, and
- 16 denotes a surface inversion region.

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FIG. 1

PRINCIPLE EXPLANATORY DIAGRAM OF FIRST INVENTION

(A)

5 SURFACE RECOMBINING VELOCITY  $S_o = \text{infinity}$

ELECTRON FLOW

BACK SURFACE INCIDENT  $h\nu$

$n^+$  DEPLETION LAYER | P REGION

10 (B)

ELECTRON

$E_C$  (CONDUCTION BAND)

$E_F$  (FERMI LEVEL)

$E_V$  (VALENCE BAND)

15 POSITIVE HOLE

--> DEPTH DIRECTION

FIG. 2

PRINCIPLE EXPLANATORY DIAGRAM OF SECOND  
INVENTION

5

(A)

ELECTRON FLOW

BACK SURFACE INCIDENT  $h\nu$

$n^+$  DEPLETION LAYER | P REGION

10

(B)

ELECTRON

POSITIVE HOLE

(C)

15

FIG. 3

PRINCIPLE EXPLANATORY DIAGRAM OF PRESENT  
INVENTION WHEN SEMICONDUCTOR SUBSTRATE IS AN n-  
TYPE

20

$P^+$  | DEPLETION LAYER | n REGION

ELECTRON

POSITIVE HOLE

FIG. 4

CONFIGURATION DIAGRAM AND ENERGY BAND DIAGRAM  
OF FIRST EMBODIMENT OF PRESENT INVENTION

5 (A)

(B)

FLOW OF SIGNAL CHARGE

10 (C)

DEPLETION LAYER | P REGION

Pn JUNCTION

ELECTRON

POSITIVE HOLE

FIG. 5

CROSS-SECTIONAL DIAGRAM OF MANUFACTURING STEPS  
OF FIRST EMBODIMENT OF PRESENT INVENTION

5 (A)

(B)

ZnS FILM

10 (C)  
CONTACT HOLE

(D)

15 (E)

FIG. 6

CONFIGURATION DIAGRAM AND ENERGY BAND DIAGRAM  
OF SECOND EMBODIMENT OF PRESENT INVENTION

5 (A)

(B)

FLOW OF SIGNAL CHARGE

10 (C)

DEPLETION LAYER | P REGION

ELECTRON

POSITIVE HOLE

FIG. 7

CROSS-SECTIONAL DIAGRAM OF MANUFACTURING STEPS  
OF SECOND EMBODIMENT OF PRESENT INVENTION

5 (A)

(B)

(C)

10

(D)

(E)

15 (F)

(G)

FIG. 8

20 MAIN PART STRUCTURE DIAGRAM OF EXAMPLE  
CONVENTIONAL PHOTODETECTORS

(a)

25 (b)